BRL-TR-3344

AD-A251 027

TECHNICAL REPORT BRL-TR-3344

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HYPERVELOCITY FIRINGS FROM A 7-INCH HARP GUN

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MAY 1992

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1992	Final Aug 90 - Sep 91

4. TITLE AND SUBTITLE

Hypervelocity Firings From A 7-Inch HARP Gun

5. FUNDING NUMBERS

PR: 1L162618AH80

6. AUTHOR(S)

Joseph W. Colburn, Carl R. Ruth, Frederick W. Robbins and Albert W. Horst

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

USA Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

BRL-TR-3344

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release - Distribution is Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Numerous approaches are being pursued to launch projectiles of various types to hypervelocities. While much recent activity has focused on the development of electric guns, research is also being conducted employing conventional chemical propulsion, both to provide a detailed understanding of the hydrodynamics of conventional hypervelocity launchers and to provide baseline data against which the various emerging propulsion concepts can be evaluated. Over the past several years, firings were conducted at the Ballistic Research Laboratory using long 120-mm gun tubes to provide velocities in the 2.5-2.7 km/s range. This report documents more recent, limited firings using a 7-inch HARP gun, launching 5-kg projectiles to a velocity exceeding 2.8 km/s. Simulations of these firings were made using the XNOVAKTC (XKTC) interior ballistic code, and a comparison of theoretical and experimental data is provided.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
Interior Ballistics, Modeling, Hypervelocity, Hypervelocity Guns	40	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

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ACKNOWLEDGMENTS

The authors would like to thank Mr. James Bowen, Mr. John "Davey" Hewitt, Mr. Dennis Meier, and Mr. James Tuerk of BRL's Range 18 for their outstanding efforts in performing the firings discussed in this report. The authors would also like to thank Mr. Fred Brandon, and Mr. Todd Rosenberger for their assistance in preparing this report.

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1. INTRODUCTION

The quest to achieve higher projectile velocities is currently of worldwide interest among the ballistics community. While terminal ballisticians debate the relative merits of velocity and mass on target, the interior ballisticians continue to pursue both conventional and novel approaches to providing launch velocities of 2.5 km/s and greater. A considerable investment is being made to develop practical electric guns, including electrothermal-chemical and electromagnetic launchers of various types. Large light gas guns and even inbore ramjet propulsion are being considered for providing very high launch velocities. However, conventional chemical propulsion appears to offer a limited but certainly achievable capability in this area. Current efforts at the Ballistic Research Laboratory include a modest study of solid propellant hypervelocity guns, aimed at providing a detailed understanding of the hydrodynamics of this environment as well as baseline data on the performance available from a conventional approach. Such a launcher may or may not offer a practical capability for tactical or strategic applications, but may indeed offer a readily available laboratory device for facilitating large-scale terminal ballistics studies at very high velocities, as well as serving as a basis of comparison to measure the progress of the more novel propulsion approaches.

The most direct methods for increasing projectile velocity in a solid propellant gun are to decrease the projectile mass, increase the length of the weapon, increase the maximum chamber pressure, and increase the energy in the propulsion charge. Any or all of these techniques may be used to produce a hypervelocity launch system. In parallel to the quest for higher velocities is the development of techniques to accurately model the performance of these guns. Most modern interior ballistic computer codes perform very well through the inventory of fielded ammunition, but when the ratio of the propulsion charge mass to the projectile mass (Charge to Mass ratio or C/M) exceeds one (1)(the value approached by most modern kinetic energy ammunition), the mechanism for transfer of energy from the burning propellant to the base of the projectile ceases to be as simple as assumed by most codes (Robbins 1986).

2. EXPERIMENTAL

2.1 Gun Hardware. At BRL, seven-inch smoothbore gun systems originally modified for use in the High Altitude Research Program (HARP) are frequently used to accelerate large masses to current ordnance velocities, or light masses to the hypervelocity regime (Bull and Murphy 1988; Evans 1966; Boyer and MacAllister 1966). These guns feature projectile travels of up to 15.25 m (600 in), maximum chamber pressures of 483 MPa (70 kpsi) and chamber volumes of 0.037 m^3

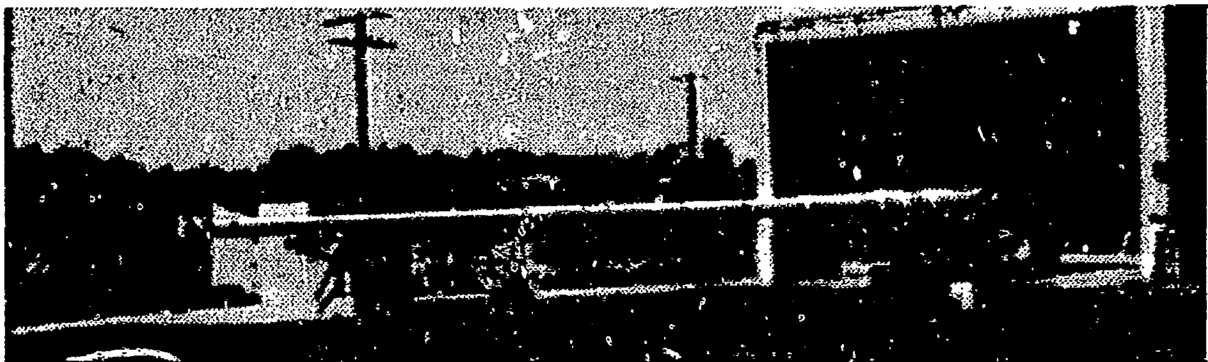

Figure 1. Seven-Inch HARP Gun at BRL's Range 18.

(2271 in^3) or more. For our tests a gun of this type was mounted in a M174 recoil on a M1 towed howitzer mount. The tube was supported just forward of the joint by a rigid mount equipped with rollers (see Figures 1 and 2). This prevented excessive tube droop and restricted tube whip during the gun firing without interfering with the recoil cycle. New inspection criteria for this series of gun condemned this tube (SN 1098) and breech soon after these experimental firings were completed.

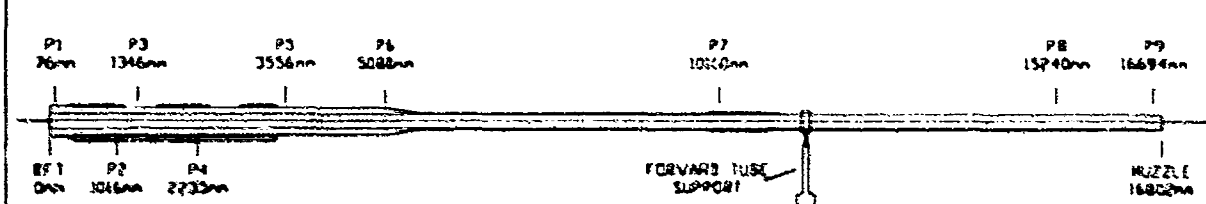

Figure 2. Seven-Inch HARP Gun Diagram (SN 1098).

2.2 Instrumentation The gun was instrumented with ten (10) piezoelectric pressure transducers (Kistler Model 6211) at nine (9) different axial locations along the tube. Transducer locations are identified in Figure 2. The transducer mounting holes were machined directly into the tube wall. Two microwave interferometers (15 GHz & 10.525 GHz) were utilized to record the motion of the projectile while in the gun tube. Two 35-mm smear cameras were used to record projectile velocity and integrity after muzzle exit. High speed film cameras and standard video cameras were utilized to record various portions of each firing.

2.3 Propelling Charge The high ratio of chamber length to chamber diameter in this gun system made the design of the ignition system critical to safe operation. Previous firings of this weapon at C/M's of up to one (1) utilized an artillery type black powder and nitrocellulose "snake" running up the center of the charge to transmit the ignition pulse to the propellant bed uniformly. Experience with 120-mm hypervelocity gun systems indicated that it would be simpler and safer to

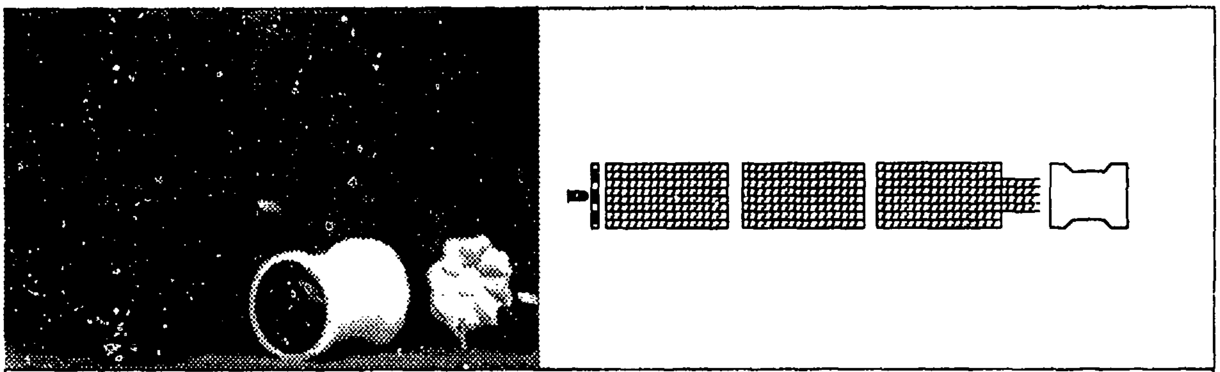

Figure 3. Charge Components & Diagram.

utilize partially cut stick propellant technology (Ruth and Horst 1991; Ruth, Robbins, and Horst 1991). The multiperforated propellant sticks have nearly the same progressivity as multi-perforated granular propellants, but since the sticks present natural flow channels to the igniter gasses, it is safe to ignite this very long charge with just a breech mounted ignition system. The charge configuration for round one is shown in Figure 3. It consisted of an M52 electric igniter, an M82 percussion primer, a 209 g (0.461 lb) class 1 black powder basepad, and 31.8 kg (70.1 lb) of JA2 stick propellant. Round two utilized 30.4 kg (67.0 lb) of the JA2 stick propellant. The JA2 was divided up into three bundles. Details of the charge configurations are presented in Table 1. XNOVAKTC, an interior ballistic computer code described later in the paper, was utilized to determine which of the lots of JA2 stick propellant on hand would yield the highest muzzle velocity with a maximum pressure of 448MPa (65 kpsi).

Table 1. Charge Component Data.

ROUND NUMBER	PROPELLANT TYPE	MASS OF BUNDLE 1	MASS OF BUNDLE 2	MASS OF BUNDLE 3	TOTAL CHARGE MASS	BASE PAD MASS
1	JA2, 19 perf, partially-cut cylindrical stick	12.864 kg	12.873 kg	6.061 kg	31.798 kg	209 g
2		14.462 kg	14.378 kg	1.584 kg	30.424 kg	

2.4 Projectiles Figure 4 shows a diagram of the 4.987 kg (10.994 lb) slug projectile utilized for the first firing. Polypropolux, a high strength, low cost plastic, was chosen as the base material for this projectile because of successful test firings in a 120-mm hypervelocity system. Since the measurement of projectile velocity was a critical part of the program, the projectile had to have a material capable of reflecting microwave energy on its front face. This requirement was satisfied with a 0.003175 m (0.125 in) thick aluminum plate attached to the front of the projectile. This projectile survived launch, but analysis of radar data led us to believe that obturation was lost early in the firing

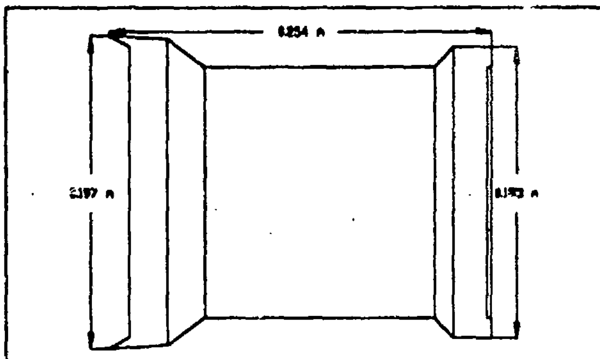

Figure 4. Projectile for Round One, 4.987 kg.

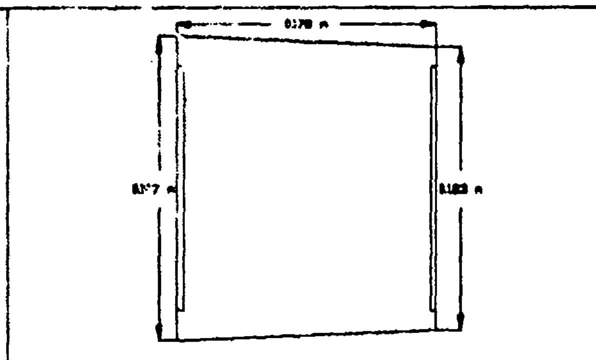

Figure 5. Projectile for Round Two, 4.988 kg.

Figure 5 is a diagram of the 4.988 kg (10.996 lb) projectile design used for the second round. The forward and rear diameters are the same as the round one projectile, but the interference fit section at the rear of the projectile presents a larger obturating surface. The rear face of the projectile was reinforced with a .00635 m (0.25 in) thick aluminum plate to provide greater protection from the propelling gasses. To maintain the same projectile mass and allow for the much wider obturator band and the additional aluminum plate, the length of the projectile was reduced. Other changes resulting from the change in projectile design are highlighted in the description of the gun firings.

3. GUN FIRINGS

3.1 Round One To maintain similitude with previously completed computer simulations, the projectile needed to be seated 1.473 m (58.0 in) from the rear face of the tube (1.397 m (55.0 in) from the forward face of the spindle). The projectile was inserted into the chamber by hand then forced into position using a hydraulic jack. Since this system did not allow precise control of the projectile motion, the projectile was finally seated at a position 1.492 m (58.75 in) from the rear face of the tube. The calculations presented in this paper were performed after the firings and reflect the true experimental seating distance. Table 2 summarizes the gun parameters for both rounds. Before loading the propulsion charge the chamber was swabbed with Keivan, a water based jelling agent traditionally used as a thickener in the food industry, which was intended to provide a cooling layer to reduce chamber erosion due to the hot burning JA2 propellant. Figure 6 shows the pressure time histories for round one.

Table 2. Gun Firing & Simulation Data.									
ROUND NUMBER	CHARGE MASS (kg)	PROJECTILE MASS (kg)	C/M	CHAMBER VOLUME (m^3)	P1 (MAX) (MPa)	P2 (MAX) (MPa)	P3 (MAX) (MPa)	P4 (MAX) (MPa)	MUZZLE VELOCITY (m/s)
1	31.798	4.987	6.38	0.04962	428	362	306	297	---
1-XKTC	31.798	4.987	6.38	0.04962	418	376	324	320	2815
2	30.424	4.988	6.1	0.04382	432	365	316	---	2818
2-XKTC	30.424	4.988	6.1	0.04382	413	---	304	---	2880

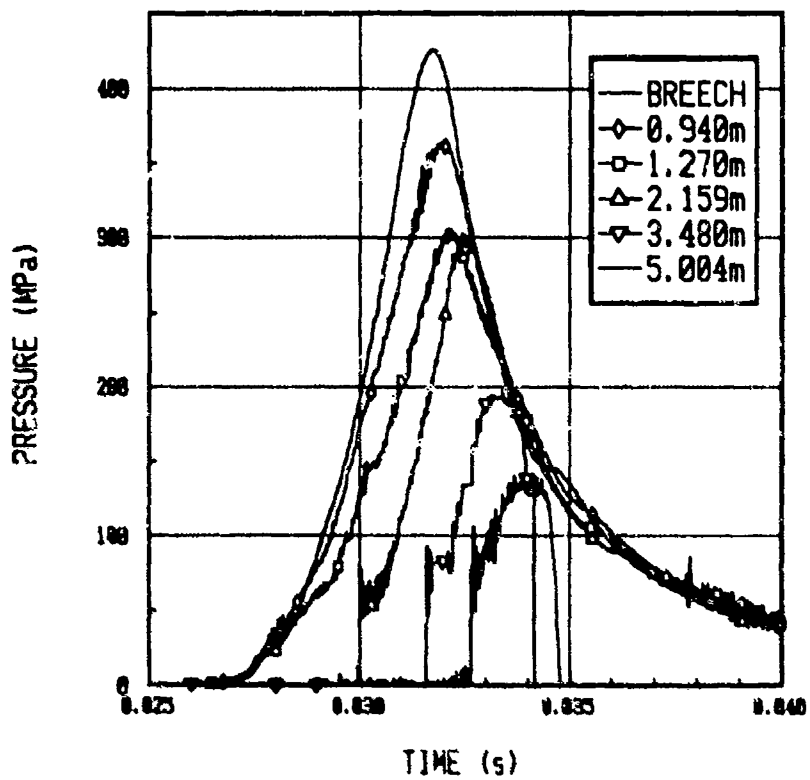

Figure 6. Round 1. Experimental Pressure Data.

3.2 Round Two An increase in the force required to seat the projectile, due to the projectile design changes made prior to round two, limited the seating distance to 1.295 m (51 in). This significantly decreased the chamber volume and required a reduction in the propulsion charge mass. Before the propulsion charge was loaded for round two the gun tube was purged with helium and sealed with a plastic diaphragm. It was hoped that this procedure would have two positive effects. The first was to reduce the resistive force encountered by the projectile by decreasing the density of the gas in the tube. Interior ballistic simulations show that a helium filled tube yields a significant increase in muzzle velocity. The greatest benefit would have been gained by evacuating the tube, but the difference between helium and vacuum is not that large, and the experimental

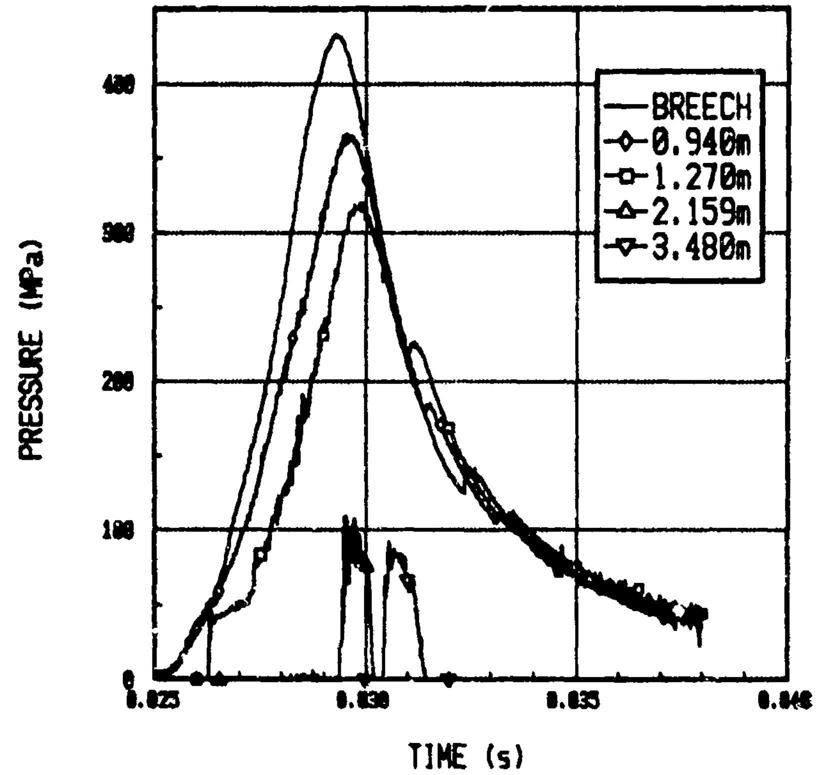

Figure 7. Round 2. Experimental Pressure Data.

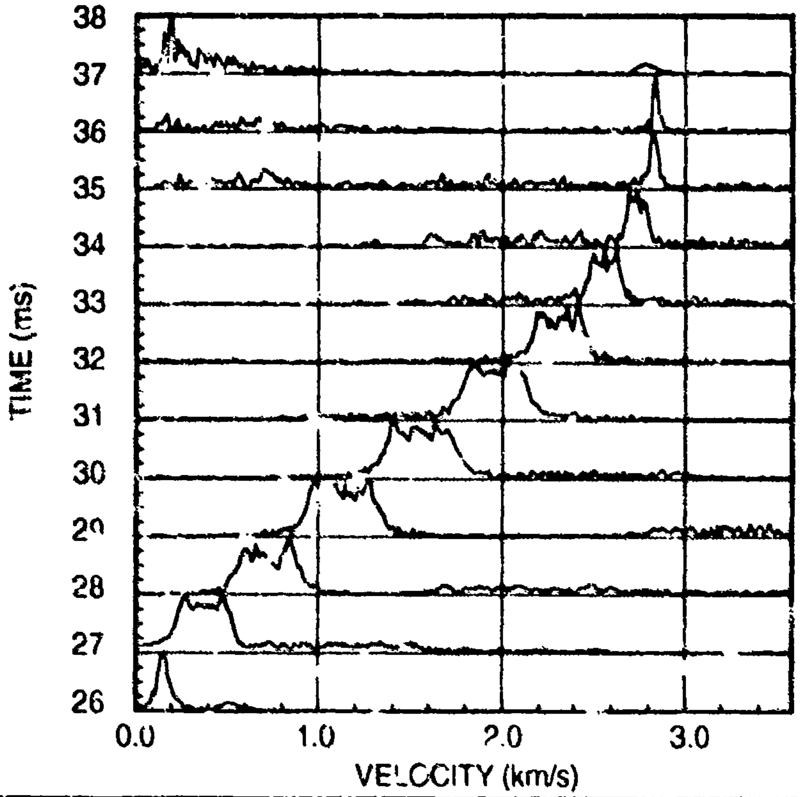

Figure 8. Round 2. Velocity Waterfall Plot.

technique for evacuating the tube is much more cumbersome than a simple gas purge. The other benefit of the helium purge was to eliminate any reactive gasses from in front of the projectile. Then if obturation failed, the fuel rich gasses would not encounter an oxidizer rich atmosphere. This technique reduces the effect of blow-by on inbore radar signals. Figure 7 shows the pressure time history for round two and Figure 8 shows the waterfall plot (velocity spectrum at discrete time steps described in the interferometry section).

3.3 Comparison Even though there were slight differences in charge mass and chamber volume (as detailed in Tables 1 and 2), the peak chamber pressures were virtually identical for both rounds. Despite the length of the charge and the simple base ignition system, pressure wave levels were minimal throughout the interior ballistic cycle. This is credited to the low axial gas flow resistance of the stick charge.

3.4 Instrumentation Performance

3.4.1 Pressure. All of the pressure transducers in the gun chamber appeared to perform well during the first firing. The downbore gages (beyond P4) only worked for a short time. This was believed to be caused by a flexural resonance phenomenon which causes high frequency, high amplitude radial strain waves in relatively thin tube walls during the passage of a hypervelocity projectile (Simkins 1987). Efforts are currently underway to attempt to isolate the transducers from this effect. During the second firing most of the chamber transducers functioned properly, but the performance of downbore gages was marginal at best. It should be noted that P3 was exposed to the initial chamber pressurization for round one; however, because of changes in the projectile for the second round, the projectile was not seated as far into the gun, and covered P3 until after the projectile moved 0.05 m (1.97 in).

3.4.2 Interferometry. On the first round the inbore 15 GHz radar signal attenuated after just a few centimeters of projectile travel. The 10.525 GHz radar, used in the downrange mode during the first round, failed to track any signal due to masking by the enormous cloud of ionized gas which followed the projectile out of the muzzle. On the second round the 15 GHz signal once again disappeared soon after the onset of projectile motion. For this round the 10.525 GHz radar was used in the inbore mode, and transmitted signal throughout the interior ballistic cycle. Figure 8 was generated by performing Fast Fourier Transforms (FFT's) on the raw interferometer data at one-millisecond intervals. No attempt was made to generate a velocity-time history from the interferometer data.

3.4.3 Cameras. All framing, video and smear cameras performed well during these firings.

4. MODELING

4.1 Background. Previous efforts to model large-caliber hypervelocity firings in a 120-mm gun (Ruth and Horst 1991; Ruth, Robbins, and Horst 1991) underscored the necessity of employing a two-phase flow interior ballistic code to simulate the hydrodynamics (particularly the pressure gradient) associated with the very high charge-to-mass ratios employed. Lumped-parameter codes continue to be useful, even at hypervelocities, for defining overall performance potential for a given gun envelope; however, limitations in the physics of the codes (again, primarily the simplified pressure gradient) typically require compromises in the input data to provide a match to observed peak pressures and velocities, leading to significant disparities in details of the inbore trajectory between theory and experiment.

In an attempt to model the 7-inch HARP firings conducted in this study, calculations were performed using the XKTC interior ballistic code (Gough 1990). XKTC is then latest version in a successful series of improvements to the NOVA code (Gough 1980), embodying the features of codes known as XNOVA (more efficient computational techniques), NOVATC (traveling charge option), XNOVAK (finite rate chemistry), and XNOVAT (numerous features for tank ammunition, including case combustion and projectile afterbody intrusion).

The basis for the NOVA family is a one-dimensional (with area change), two-phase, unsteady flow representation of the interior ballistic cycle. The balance equations describe the evolution of macroscopic flow properties accompanying changes in mass, momentum, and energy arising out of interactions associated with combustion, interphase drag, and heat transfer. The state variables are to be thought of as averages of local microproperties, with intractable details of the microflow related to the macroscopic variables by means of empirical correlations. Functioning of the igniter is specified as a predetermined mass injection rate as a function of space and time. Flamespread then follows from axial convection, with the propellant responding as an inert material until a surface temperature ignition criterion is met; regression then ensues based on a conventional aP^n burning rate law, unless the finite rate chemistry option is invoked (not used in this study). The governing equations are solved by the method of finite differences with an explicit allowance for discontinuities in the state variables at internal boundaries defined by the ends of the propellant increments.

4.2 Round One. Prior to the actual firings, a nominal XKTC input data base (see Appendix) was assembled based on the physical dimensions and properties of the system components, an assumed projectile seating distance, and other data (e.g., propellant burning rate, bore resistance profile) developed for and modified from previous hypervelocity firings (Robbins, Ruth, and Horst, not yet published). Simulations were performed using these data to identify the best available propellant lot and to estimate a charge weight that would provide maximum performance at a peak chamber pressure at about 414 MPa (60 kpsi), a recommended safe limit for our tube.

After the first firing, the data base was altered to reflect actual component masses and loading data (e.g., projectile seating distance). The first simulation performed using these data provided an adequate match to overall performance data (e.g., peak chamber pressure) but a somewhat disappointing representation of details of the pressure-time curves as well as the times at which the projectile passed the downbore pressure gages.

One of the essential features of a multiphase flow interior ballistic code is treatment of interactions between the solid and gas phases, such as the interphase drag. This drag force is usually calculated in such codes by reference to empirically based correlations for fixed and fluidized beds of particles of approximately the correct shape at appropriate Reynolds numbers. For the

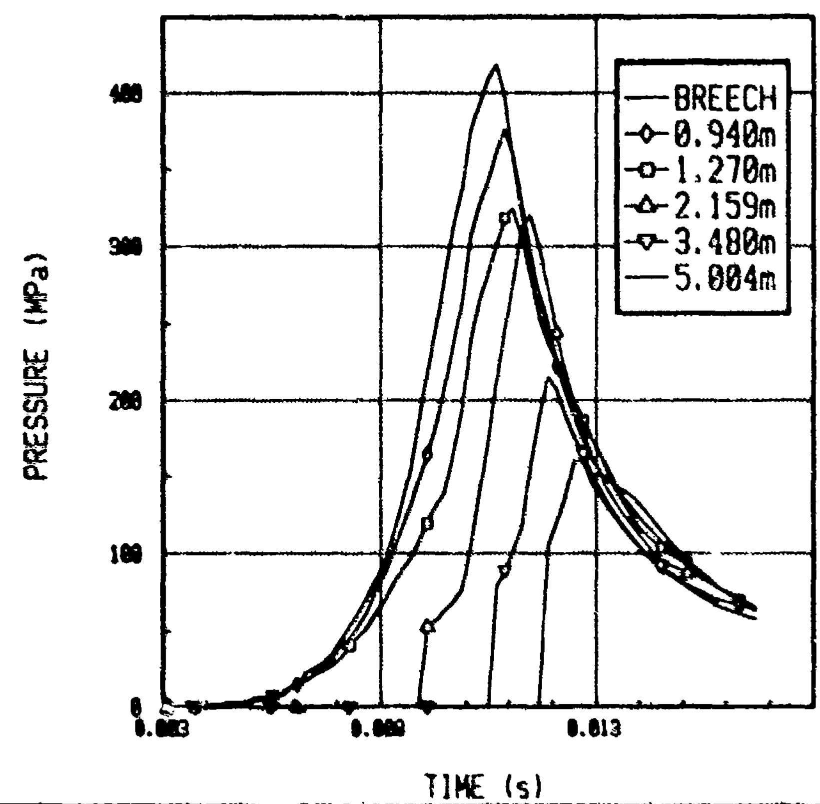

Figure 9. Round 1. Calculated Pressure Data.

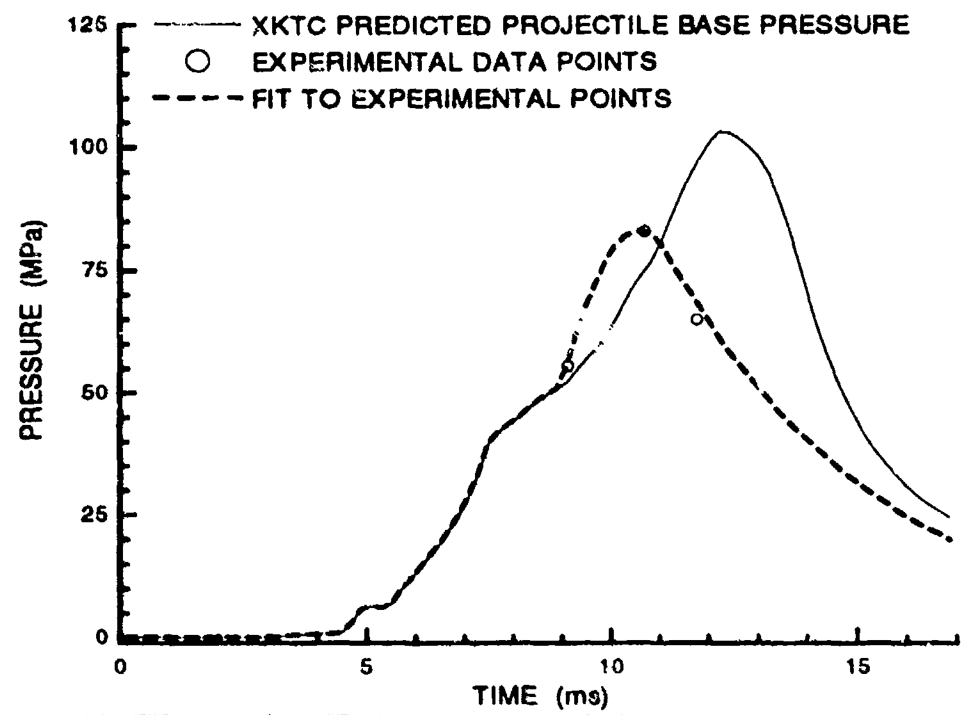

Figure 10. Round 1. Calculated Base Pressure Data.

partially cut stick propellant employed in the subject firings, while it is clear that the propellant initially offers the geometric characteristics of a bundle of stick propellant and later transforms to a (largely fluidized) bed of what is essentially granular propellant, the timing of this event is unknown. The XKTC code makes the assumption that this transformation begins to occur when motion of the projectile has provided sufficient additional chamber volume for the separated propellant pieces to rotate. Owing to the limitations and uncertainties of this assumption, additional simulations were performed varying the time period over which this transition occurs.

The final parameters selected (also listed in the Appendix) resulted in the pressure-time curves shown in Figure 9, providing a good match to the shape of the experimental curves and the times at which the projectile passed the first three downbore pressure gages, with the predicted pressure within 10 MPa of the measured value. No verification of the predicted muzzle velocity was possible as this measurement failed.

Figure 10 displays a simulated projectile base pressure-time curve, along with values for the maximum pressures recorded by the first three downbore gages. We note that while good agreement is seen for the first two locations, the measured value for the third falls far below the simulated base pressure at that position. Given the damage to downbore gages beyond the third position (possibly from tube flexural resonance), data recorded at this third position was also considered suspect. A quick check on the plausibility of these data was performed by constructing a simple model of the base pressure curve based on the early portion of the calculated curve "spliced" to experimental data from all three downbore gages. A comparison of predicted velocities based on this crude model and the XKTC simulation itself (which provided a good fit to the experimental pressures measured at the first two downbore gages but not the third) revealed a difference of some 600 m/s, the profile including the data from the third downbore gage predicting a velocity a velocity of 2479 m/s, far below both theory and experiment as presented in Table 2. It was thus concluded that the experimental pressure measured by the third downbore gage should be discounted.

4.3 Round Two. As mentioned in an earlier section of this report, changes were introduced in the configuration of the projectile for the second firing, and an XKTC calculation was performed reflecting these changes to select a charge mass for the test. The input data are again recorded in the Appendix, and the pressure-time curves resulting from the simulation are presented in Figure 11. The simulation, however, assumed pure helium in the tube ahead of the projectile, a situation that was not likely at the time of the firing, and did not fully account for the influence of the change in projectile configuration on the bore resistance. These factors likely account for some disparity

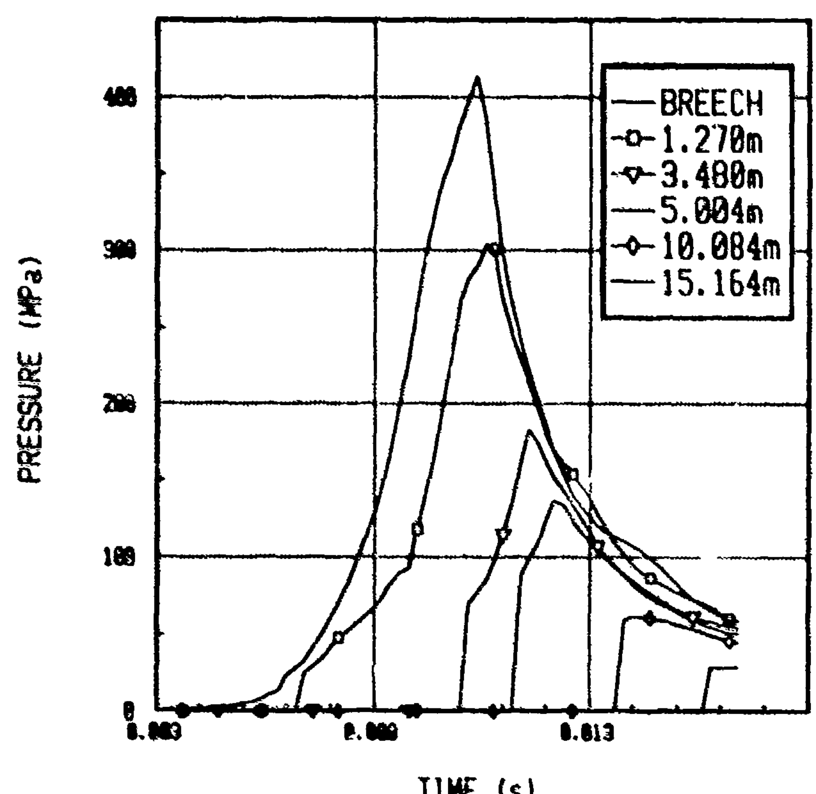

Figure 11. Round 2. Calculated Pressure Data.

between the prediction and the measured values (which this time includes a successful measurement of the projectile velocity), as presented in Table 2. Further, the quality of virtually all recorded downbore pressure curves precluded their use as anything but event markers in evaluating the accuracy of the simulation.

5. CONCLUSIONS

Significant masses can be propelled to velocities in excess of 2.5 km/s utilizing a conventional mode of solid propulsion. While the high charge to mass ratio leads to significant pressure gradients ultimately limiting achievable velocities (Heiser 1980), firings conducted under this program verify the practicality of such launchers for use in laboratory applications and perhaps even suggest the potential for certain weapon applications as well. Further, the XKTC multiphase flow interior ballistic code appears to offer a useful capability for charge design for such launchers.

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APPENDIX

INPUT FOR XKTC SIMULATION OF 7-INCH HARP GUN FIRINGS

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ROUND ONE, PRELIMINARY SIMULATION

```
175 MM MOD GUN 1098 HARP
TTFFTTT      1 6 0    00    1
 55  -3   0 3500
10.0     604.0    0.0001   2.0      0.05      0.01       0.0001     0.0001
1000  100 1100  100 1500  100
 8   9   6   5   0   0   1   2   0   0   0   8   0
529.     14.7     28.896   1.4
529.0
JA2 19PF LOT 792-39 1.0      55.75     70.1      .05763
 -9  .587   0.036     1.5       19.                        1
.1      0.01     8.0      7.0      1.0      1.0
40000.    1.0      41754.             .5
6000.   .0010154 .8608     100000.  .00048009 .9469    0.0      800.
.0277      .0001345  .6
20372433. 24.8226  1.2268    26.98
9967547.  30.93     1.221    23.00
0.       .008      .012      .015      .05       .0510    .052       .0525 .0725
0.0       .99       1.00      12.0      12.1      21.3
0.0       0.0       0.0       0.0       0.0       0.0
75.       75.       0.0       0.0       0.0       0.0
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0.0      4.240     41.2      4.240     49.15     3.806    85.00     3.79
88.6      3.655     114.65   3.65      120.      3.65     659.1     3.65
0.0       200.      28.      300.      38.      1000.     45.       300.
615.      300.
1.4       14.7      550.      28.9
0.05      0.43      10.       1.25
7.77      0.0228    .7 55.75      10.994    44.0      0.000
0.0       37.       50.       85.       137.      197.      654.25     50.
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ROUND ONE, FINAL SIMULATION

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1000  100 1100  100 1500  100
 8   9   6   5   0   0   3   2   0   0   0   8   0   0   0   0
529.     14.7     28.896    1.4
529.0
JA2 19PF LOT 792-39 1.0      22.0     28.362    .05763
 -9  .587   0.036     1.5      19.                          1
.1      0.0      10.0      9.0      2.0      1.0
40000.    1.0      41754.            .5
6000.   .0010459  .8608    100000.  .00049449 .9469    0.0      800.
.0277      .0001345  .6
20372433. 24.8226   1.2268    26.98
JA2 19PF LOT 792-39 22.0     43.0     28.380    .05763
 -9  .587   0.036     1.5      19.                          1
.1      0.01     8.0       6.0      2.0      2.0
40000.    1.0      41754.            .5
6000.   .0010459  .8608    100000.  .00049449 .9469    0.0      800.
.0277      .0001345  .6
20372433. 24.8226   1.2268    26.98
JA2 19PF LOT 792-39 43.0     55.75    13.361    .05763
 -9  .587   0.036     1.5      19.                          1
.1      0.01     7.0       5.0      2.0      2.0
40000.    1.0      41754.            .5
6000.   .0010459  .8608    100000.  .00049449 .9469    0.0      800.
.0277      .0001345  .6
20372433. 24.8226   1.2268    26.98
9967547.  30.93     1.221     23.00
0.      .008     .012     .015     .05      .0510    .052     .0525 .0725
0.0     .99      1.00     12.0     12.1     21.3
0.0     0.0      0.0      0.0      0.0      0.0
75.     75.      0.0      0.0      0.0      0.0
00.     00.      0.0      0.0      0.0      0.0
0.      0.       0.0      0.0      0.       0.
0.      0.       0.0      0.0      0.       0.
0.      0.       0.       0.       0.       0.
0.      0.       0.       0.       0.       0.
0.0     0.0      0.0      0.0      0.0      0.0
0.0     0.0      0.0      0.0      0.0      0.0
0.0     4.240    41.2     4.240    49.15    3.806    85.00    3.79
88.6    3.655    114.65   3.65     120.     3.65     659.1    3.65
0.0     500.     28.      500.     38.      3000.    45.      500.
615.    500.
1.4     14.7     550.     28.9
0.1     0.43     10.      1.25
7.77    0.0228   .7
55.75   10.994   44.0     0.000
0.0     37.      50.      85.      137.     197.     654.25   50.
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ROUND TWO, PRELIMINARY SIMULATION

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175 MM MOD GUN 1098 HARP
TTFFTTT      1 6 0    00    1
 56  -3   0 3500
10.0     611.0    0.0001   2.0      0.05     0.01     0.0001    0.0001
1000  100 1100  100 1500  100
 8   9   6   5   0   0   3   2   0   0   0   8   0   0   0   0
529.     14.7     28.896   1.4
529.0
JA2 19PF LOT 792-39 1.0      22.5      31.884    .05763
 -9  .587   0.036     1.5       19.                        1
.1      0.0      10.0     8.0      2.0      2.0
40000.    1.0      41754.          .5
6000.   .0010459  .8608    100000.  .00049449 .9469    0.0      800.
.0277      .0001345  .6
20372433. 24.8226   1.2268    26.98
JA2 19PF LOT 792-39 22.5     44.0      31.698    .05763
 -9  .587   0.036     1.5       19.                        1
.1      0.01     8.0      6.0      2.0      2.0
40000.    1.0      41754.          .5
6000.   .0010459  .8608    100000.  .00049449 .9469    0.0      800.
.0277      .0001345  .6
20372433. 24.8226   1.2268    26.98
JA2 19PF LOT 792-39 44.0     48.00     3.492     .05763
 -9  .587   0.036     1.5       19.                        1
.1      0.01     7.0      5.0      2.0      2.0
40000.    1.0      41754.          .5
6000.   .0010459  .8608    100000.  .00049449 .9469    0.0      800.
.0277      .0001345  .6
20372433  24.8226   1.2268    26.98
9967547.  30.93    1.221    23.00
0.      .008     .012      .015     .05      .0510   .052      .0525 .0725
0.0      .99      1.00      12.0     12.1     21.3
0.0      0.0      0.0       0.0      0.0      0.0
75.      75.      0.0       0.0      0.0      0.0
00.      00.      0.0       0.0      0.0      0.0
 0.       0.      0.0       0.0      0.       0.
 0.       0.      0.0       0.0      0.       0.
 0.       0.       0.        0.      0.       0.
 0.       0.       0.        0.      0.       0.
0.0      0.0      0.0       0.0      0.0      0.0
0.0      0.0      0.0       0.0      0.0      0.0
0.0      4.240     41.2     4.240    49.15    3.806    85.00    3.79
88.6     3.655     114.65   3.65     120.     3.65     659.1     3.65
0.0      200.     28.      300.     45.      3000.    45.      300.
615.     300.
[illegible]      14.7     550.     4.0
0.05     0.43     7.       6.0
7.77     0.0228   .7
48.00     10.994   44.0     0.000
0.0      50.      137.     197.     397.     597.     654.25    50.
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